Statistical Evaluation of Instruments Designed to Measure Volumetric Water Content of Soilless Container Media

R. C. Hansen, J. C. Christman, R. C. Derksen

Abstract. *If decisions are to be made concerning when and how much to irrigate container-grown plants, then procedures for measuring the accuracy and reliability of Volumetric Water Content (VWC) sensors should be developed. Three statistical properties were used to characterize the quality of VWC sensor data for this study: (1) bias, (2) variance, and (3) measurement system discrimination. The objectives of the tests reported here were to evaluate the measurement capability of three commercially available moisture sensors. Based on standardized repeatability and reproducibility measurement procedures for determining variance, estimated standard deviation (measurement error) for the WET Sensor was 2.11% VWC while the HydroSense and the ThetaProbe were 1.21% and 1.43%, respectively. Bias readings for all three instruments were 3% to 5% below a 30% reference value. Evaluation of discrimination in terms of measurement system acceptance calculations found all three sensors were well within a 10% to 30% guideline that compares measurement error to the range of expected values to be discriminated.*

Keywords. *Microirrigation, Sensors, Nursery crops, Electrical conductivity.*

Soilless container mediums are used to grow many crops in greenhouses and nurseries. While container-grown greenhouse crops are housed within protected environments, many container-grown nursery crops are set outdoors in custom designed beds. Typically, growers make irrigation decisions based on subjective observation of their crops. Ideally, “When to irrigate?” and “How much to irrigate?” container-grown crops could be enhanced with the use of reliable moisture sensors.

Many moisture-sensing devices are commercially available for measuring and monitoring the volumetric water content (VWC) of naturally occurring field soils. Seyfried and Murdock (2004) recently determined the accuracy and precision of a soil water sensor in four soil conditions. A few of these devices have recently been adapted so they can measure the VWC of soilless container mediums. Many sensors respond to the dielectric constant of the combination of the water and the container medium matrix. Since the dielectric constant of water (~81) is more than one order of magnitude higher than dry soilless container media (typically 3 to 5) and air (typically 1), the dielectric constants of irrigated soil and/or soilless mediums are primarily dependent upon their water content. Unique, customized sensor calibrations are required prior to measuring the VWC of organic mediums since they are normally more porous than mineral soils. If decisions are to be made concerning when and how much to irrigate container-grown plants, then procedures for measuring the accuracy and reliability of VWC sensors should be developed.

A measurement system can be defined as the complete process used to obtain data. This process includes measurement procedures, sensors, gauges, data-recording devices, associated software, and the persons doing the measuring (Down et al., 1995). The effects of a variable environment must be noted. The benefits attained by using a data-based procedure for evaluating the capability of manufacturing processes or irrigation equipment to meet specifications are largely determined by the quality of the measurement data obtained. The quality of measurement data is defined by the statistical properties of multiple measurements observed while using sensors under stable operating conditions.

Three statistical properties are commonly used to characterize the quality of data: (1) bias, (2) variance, and (3) measurement system discrimination. Bias is another term for accuracy that avoids confusion about the meaning of the term “accurate.” Bias is defined as the difference between the average of 10 to 20 measurements of a designated quality characteristic and its true value. For certain types of measurements, this true value is traceable to a standard

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retained at the National Institute of Standards and Technology in Washington, D.C. Measurement system variance can be determined by calculating: (1) repeatability and (2) reproducibility (Down et al., 1995). Repeatability is referred to as equipment variation. It is an assessment of the ability of a gauge or sensor to repeat a measurement in the same location on the same part under the same conditions. Meanwhile, reproducibility is identified with appraiser variation. It is an assessment of the effect of more than one appraiser (operator) on measurement system variation. Finally, measurement system discrimination refers to the capability of the measurement process to faithfully detect small changes in a measured characteristic (Down et al., 1995). Discrimination is also known as gauge resolution.

The primary purpose of this article was to establish a statistical procedure for evaluating and comparing the measurement capability of VWC sensors. The objectives of the tests to be reported here were to evaluate the measurement capability of three commercially available moisture sensors that are designed to detect the volumetric water content of potting mediums. Treatments were designed to measure the effects of adding nutrients to irrigation water solutions and the associated impacts of high electrical conductivity (EC) levels. Statistical properties that were evaluated included bias, repeatability, reproducibility, and discrimination.

Materials and Methods

Description of Sensors

HydroSense

The HydroSense Volumetric Water Content measurement device (Campbell Scientific, Inc., Logan, Utah) uses the media physical property dielectric permittivity to estimate the VWC. The travel time of electromagnetic energy along a wave guide is dependent on the dielectric permittivity of substances surrounding the wave guide. The HydroSense probe consists of two rods 12 cm long that act as a wave guide. Rods that are 20 cm long are also available, but were not used in this experiment. An applied signal travels to the end of the rods and reverses its direction of travel. The time of travel for this signal is then determined in milliseconds. This millisecond reading is transformed into a VWC reading based on calibration results that are specific to the organic medium to be measured.

ThetaProbe

The ThetaProbe ML2x sensor (The Macaulay Land Use Research Institute, Aberdeen, U.K.) generates a 100-MHz signal that is applied to a specifically designed internal transmission line that extends into a soil and/or a soilless media by means of an array of four individual rods approximately 6 cm in length. The impedance of this array varies with the impedance of the soil, which has two components: the apparent dielectric constant and the ionic conductivity. The impedance of the four-rod array affects the reflection of the signal, and these reflections combine with the applied signal to form a voltage standing wave along the transmission line. The output of the Theta Probe is an analogue voltage proportional to the difference in amplitude of this standing wave at two points. The result is a sensitive and precise measure of VWC.

WET Sensor

The Delta T WET Sensor type WET-1 (Delta-T Devices Ltd., Cambridge, England) is a multi-parameter sensor consisting of three parallel rods 6.35 cm in length. The unit is designed for use in soils, composts, and other artificial growing mediums. A 20-MHz signal is applied to the central rod that produces a small electromagnetic field within the medium. The sensor converts measured dielectric properties into VWC via calibration tables. The WET Sensor is also capable of simultaneously measuring the EC of the water solution stored in the pore space within a medium and the temperature of the medium.

A HH2 Moisture Meter (Delta-T Devices Ltd., Cambridge, England) was used for readout and data storage for the Theta Probe and the WET Sensor. It is a hand-held unit that is supplied with a variety of calibration curves. For the measurements reported here, the same organic media calibration curve was used for the ThetaProbe and the WET Sensor.

Procedure for Measuring Instrument Bias

Nine identical polyethylene pots, typically used for growing greenhouse crops, were selected for these measurements. One pot was lined with a plastic garbage bag and filled with water to calculate the container's volume when it was nearly full. The pot was found to hold 2000 mL of water when filled to a mark that was placed ~2.5 cm below the top of the rim. The pot was emptied and the garbage bag removed. The pots were then labeled with numbers from 1 through 9.

Premier Pro-Mix 'BX' potting medium was used for these tests. It is a commercially available, general-purpose, peat-based mix that is used for a wide variety of plant species (Hummert International, Earth City, Mo.). The medium was oven dried at 104°C for 96 h to assure that the water was removed. Then it was poured into all nine pots and packed firmly until they were filled to the 2000-mL level. The nine filled pots were set out on a workbench in three sets of three pots. The contents of one set of three pots were dumped into a mixing bowl with 600 mL of tap water. The EC of the tap water was 0.4 mmhos/cm. The water and medium were mixed by hand for about 5 min to distribute the water uniformly throughout the mix. Once the mix appeared to be uniform in water content, the medium was repacked to the same mark in the same three pots. This same procedure was followed for the second set of three pots except calcium nitrate was added to the tap water resulting in a nutrient solution with an EC reading of 1.6 mmhos/cm. Similarly, calcium nitrate was added to the tap water used for the third set of three containers resulting in an EC reading of 5.0 mmhos/cm. As a result of adding 600 mL to a 2000-mL container, the VWC master or reference value for each pot was 30%.

Fifteen measurements were completed with the HydroSense instrument for each EC level. These measurements were obtained by having one experienced operator measure each pot five times. The operator took one measurement by vertically probing the center of a pot followed by four measurements evenly spaced 90 degrees apart 5 cm out from the center. The same procedure was then followed for the second and third pot in the set leading to 15 repetitive measurements. Similarly, 15 measurements were completed for the Theta Probe and the WET Sensor following the same procedure. The capability of each sensor was appraised at all three levels of EC for a total of nine appraisals of instrument bias.

Procedure for Measuring Instrument Repeatability, Reproducibility, and Discrimination

Ten identical, polyethylene pots were selected for these measurements. Again, one pot was lined with a plastic garbage bag and filled with water to calculate the container's volume when it was nearly full. The pot was found to hold 2500 mL of water when filled to a mark that was placed near the rim. The pot was emptied and the garbage bag removed. The pots were then labeled with numbers from 1 through 10.

Premier Pro-Mix 'BX' potting medium was again used for these tests. After drying, the medium was poured into each of the 10 pots and packed firmly until they were filled to the 2500-mL level. A known quantity of water was added to the medium in each container by dumping it into a mixing bowl, after which the water and medium were mixed by hand to distribute the water uniformly throughout the mix. Once the mix appeared to be uniform in water content, the medium was repacked to the same mark in the pot. Unlike the bias appraisal procedure, where all containers were set at a reference value of VWC = 30%, these pots were filled with an array of water contents ranging from 5% to 50% VWC while using water solutions with randomly selected, variable levels of calcium nitrate concentrations. Guidelines for the instrument assessment procedure recommend that a broad spectrum of the characteristic to be measured (VWC in this case) be included in the array of pots from the smallest to the largest expected values (Down et al., 1995). Table 1 shows the quantities of water solution added to the potting medium along with corresponding solution EC levels by pot number.

Table 1. Quantity of water solution added to each 2500-mL pot, VWC and associated EC. [a]

Pot No.	Quantity of Solution Added (mL)	Volumetric Water Content (%)	EC of Solution (mmhos/cm)
1	250	10	3.94
2	500	20	1.66
3	375	15	1.29
4	625	25	3.22
5	125	5	2.62
6	750	30	1.94
7	875	35	2.29
8	1000	40	0.36
9	1250	50	2.48
10	230	9	3.05

[a] Used for repeatability, reproducibility, and discrimination assessments.

Three instrument operators designated Appraiser A, Appraiser B and Appraiser C probed all 10 pots using the HydroSense in random order as shown in table 2. For each measurement event, the operators probed each pot vertically three times from which an average VWC reading was calculated. This set of measurements was designated Trial 1. Next, the three appraisers repeated the same measurements for all ten pots in a newly defined random order. This was designated Trial 2. Finally, a third series of measurements were completed and recorded as Trial 3. This entire three-trial process was repeated for the Theta Probe and then for the WET Sensor. Random numbers were reordered for each instrument assessment.

A record of measurements for three appraisers using the HydroSense, ThetaProbe, and the WET Sensor are shown in tables 6, 7, and 8. Each tabulated measurement was the average of three readings that resulted from three probings in each pot. After all three sets of randomly ordered measurements (table 2) were completed (Trial Nos. 1, 2, and 3), readings were reordered sequentially and tabulated by pot number and trial number. Next, the readings for the three trials were averaged for each appraiser and pot number. Then the differences between the highest and lowest readings were recorded as the range. Finally the 10 averages and the 10 range values were averaged and recorded in the last column.

Results and Discussion

Instrument Bias

Records of measurements collected during the instrument bias study (December 2003) are shown in table 3. Since the mixes actually contained volumetric water contents equal

Table 2. Example random order used for sequencing appraisers' trials and pot numbers.

Operator A:________			Operator B________			Operator C: ________		
Trial No.			Trial No.			Trial No.		
1	2	3	1	2	3	1	2	3
4	4	3	4	3	6	7	3	9
8	10	9	6	9	7	8	9	8
2	9	1	10	1	4	9	7	6
9	3	10	1	10	5	6	8	7
6	5	2	9	2	3	2	1	3
5	1	8	2	8	10	3	10	4
1	7	4	3	4	9	10	4	2
10	2	6	7	6	2	4	6	10
7	6	5	8	5	8	1	5	1
3	8	7	5	7	1	5	2	5
Random Operator Trial Order								
3	5	8	2	6	7	1	4	9

Table 3. Record of VWC measurements comparing instrument bias as affected by three levels of EC in the water solution. The actual VWC of the mix in each pot was 30%.

Reading No.	Volumetric Water Content (%)								
	HydroSense			ThetaProbe ML2x			WET Sensor		
	Mix No. 1[a]	Mix No. 2[b]	Mix No. 3[c]	Mix No. 1	Mix No. 2	Mix No. 3	Mix No. 1	Mix No. 2	Mix No. 3
1	24.1	24.1	31.3	24.3	24.1	27.4	22.4	23.4	32.1
2	25.2	24.1	34.1	25.2	24.4	30.2	25.1	26.5	30.6
3	25.2	25.2	32.7	22.8	24.6	31.7	28.1	28.6	30.8
4	25.2	26.3	32.7	26.3	25.6	31.1	27.8	27.5	30.5
5	24.1	28.1	33.4	24.1	26.4	29.3	24.6	26.9	28.1
6	24.1	28.1	33.4	22.4	26.1	26.5	23.1	29.9	34.2
7	23.0	26.3	32.7	22.7	27.2	29.4	24.6	29.1	35.2
8	24.1	26.3	32.7	25.1	23.0	28.2	26.0	27.9	34.2
9	24.1	24.1	32.0	25.7	24.0	27.7	24.9	26.9	32.5
10	23.0	24.1	31.3	24.2	26.2	28.2	23.7	26.0	34.0
11	25.2	25.2	33.4	25.4	25.3	31.0	25.2	24.3	29.8
12	25.2	26.3	29.8	26.1	28.7	30.9	27.8	22.6	28.1
13	24.1	26.3	34.1	26.0	25.5	30.2	24.3	24.7	29.3
14	26.3	27.2	34.1	27.3	26.9	34.2	27.3	26.4	33.4
15	25.2	27.2	30.5	24.9	27.2	33.6	27.1	27.1	31.8

[a] Mix No. 1: EC of water solution added = 0.40 mmhos/cm.
[b] Mix No. 2: EC of water solution added = 1.60 mmhos/cm.
[c] Mix No. 3: EC of water solution added = 5.00 mmhos/cm.

to 30%, ideally every reading should be close to 30.0. Generally, the readings were 4% to 5% below the reference value for Mix No. 1 and Mix No. 2 while being higher than 30% for Mix No. 3.

Table 4 shows the mean values and sample standard deviations of the 15 readings logged for each instrument and mix number. For all three instruments, average VWC readings increased as the EC of the water solution increased. In addition, sample standard deviations increased as the EC of the water solution increased with the exception of Mix No. 3 for the HydroSense. Average ThetaProbe readings over all three mixes were significantly less than average readings for the HydroSense and the WET Sensor. Meanwhile, average readings for the HydroSense and the WET Sensor were not significantly different. These results verified field experience reported by Hansen et al. (2003). Increased potting medium solution EC generally leads to more erratic VWC sensor readings. Sample standard deviations for the HydroSense readings were typically less than readings for the other two sensors. The HydroSense had the advantage of sensing a cylindrical cross section of the potting medium that was twice as long at the other two sensors leading to a larger sample and therefore less variation.

Instrument bias values are summarized in table 5. Bias was calculated by subtracting the reference value (VWC = 30%) from the average values for each instrument and mix number. Minimum absolute values for bias were expected while using tap water at EC = 0.4 mmhos/cm while higher values were expected when using water solutions at EC = 5.0 mmhos/cm. The actual results indicate the opposite. Bias values for Mix No. 1 ranged from -4.50% to -5.50% while values for Mix No. 2 ranged from -3.50% to -4.30%. When the tap water was amended with calcium nitrate leading to an EC = 5.0 mmhos/cm, the bias was zero for the ThetaProbe, a +2.6% for the HydroSense and a +1.6% for the WET Sensor. Bias values averaged -5.07 for Mix No. 1 and -3.97 for Mix No. 2. Meanwhile, the average bias for Mix No. 3 was +1.40%.

A plausible explanation for this may be that the potting medium used for these tests did not retain as much water as the generic organic medium the gauge manufacturers used at the time the sensors were calibrated at the factory.

The impacts of EC on bias results are graphically compared in figure 1. When mediums mixed with higher EC solutions were measured, the EC compensated for the lower than expected water content of the porous, organic medium.

Table 4. Comparison of VWC means and sample standard deviations for three instruments. The actual VWC of the mix in each pot was 30%.

Instrument	Volumetric Water Content (%)						
	Mean (n = 15)				Sample Standard Deviation		
	Mix No. 1[a]	Mix No. 2[b]	Mix No. 3[c]	Average[d]	Mix No. 1[a]	Mix No. 2[b]	Mix No. 3[c]
HydroSense	24.6	25.9	32.6	27.7a	0.91	1.39	1.34
ThetaProbe	24.8	25.7	30.0	26.8b	1.42	1.50	2.21
WET Sensor	25.5	26.5	31.6	27.9a	1.81	2.06	2.27
Average[d]	25.0a	26.0b	31.4c		1.38	1.65	1.94

[a] Mix No. 1: EC of water solution added = 0.40 mmhos/cm.
[b] Mix No. 2: EC of water solution added = 1.60 mmhos/cm.
[c] Mix No. 3: EC of water solution added = 5.00 mmhos/cm.
[d] Means followed by the same letter are not significantly different (α = 0.05).

Table 5. Comparison of bias results for three instruments.

Instrument	Volumetric Water Content (%) Mix No. 1[a]	Mix No. 2[b]	Mix No. 3[c]
	December 2003		
HydroSense	−5.50	−4.10	2.60
ThetaProbe	−5.20	−4.30	0.00
WET Sensor	−4.50	−3.50	1.60
Average	−5.07	−3.97	1.40

[a] Mix No. 1: EC of water solution added = 0.40 mmhos/cm.
[b] Mix No. 2: EC of water solution added = 1.60 mmhos/cm.
[c] Mix No. 3: EC of water solution added = 5.00 mmhos/cm.

All three sensors responded similarly to additional EC with the HydroSense showing the greatest impact and the ThetaProbe the least.

INSTRUMENT REPEATABILITY, REPRODUCIBILITY, AND DISCRIMINATION

A first glimpse of an instrument's capability to repeat measurements came from reviewing the range values shown in tables 6, 7, and 8. While using the HydroSense, Appraiser C obtained the same reading for all three trials while measuring the VWC for Pot No. 5 (table 6). Therefore, the range of the three trials was zero. The largest range occurred when Appraiser A used the HydroSense to measure the VWC in Pot No. 9. The difference between the largest reading and the smallest reading was 7.3%. The averages in the last column of tables 6, 7, and 8 provide an opportunity to assess variation among the three appraisers while they used the same instrument. The largest difference (VWC = 2.7%) was found between Appraiser A and Appraiser C while using the WET Sensor (table 8).

Equipment Variation (EV) – Repeatability

According to Down et al. (1995), equipment variation (EV) is based on range values resulting from readings obtained by each appraiser during three trials, for example, the capability of the HydroSense to repeat the same reading while measuring the same pot. The average of 10 range values (Pot No. 1 through 10) becomes the basis for estimating the equipment variation for each instrument. The following calculations are based on results obtained for the HydroSense as recorded in table 6.

The grand average $(\overline{\overline{R}})$ of the average range values for all three appraisers $(\overline{R}_A, \overline{R}_B, \overline{R}_C)$ is calculated first.

$$\overline{\overline{R}} = \frac{\overline{R}_A + \overline{R}_B + \overline{R}_C}{3} = \frac{1.9\% + 1.4\% + 1.1\%}{3} = 1.47\% \quad (1)$$

The equipment standard deviation is estimated using d_2^* as defined b y Duncan (1972):

$$\hat{\sigma}_e = \frac{\overline{\overline{R}}}{d_2^*} = \frac{1.47\%}{1.69} = 0.87\% \quad (2)$$

The d_2^* factor is dependent on the sample size, the number of containers measured, and the number of appraisers. For these tests the sample size (number of trials) was three (n = 3), the number of containers was 10, and the number of appraisers was three. In a table developed by Duncan (1974) to define the d_2^* factor, it is clear that as the sample size

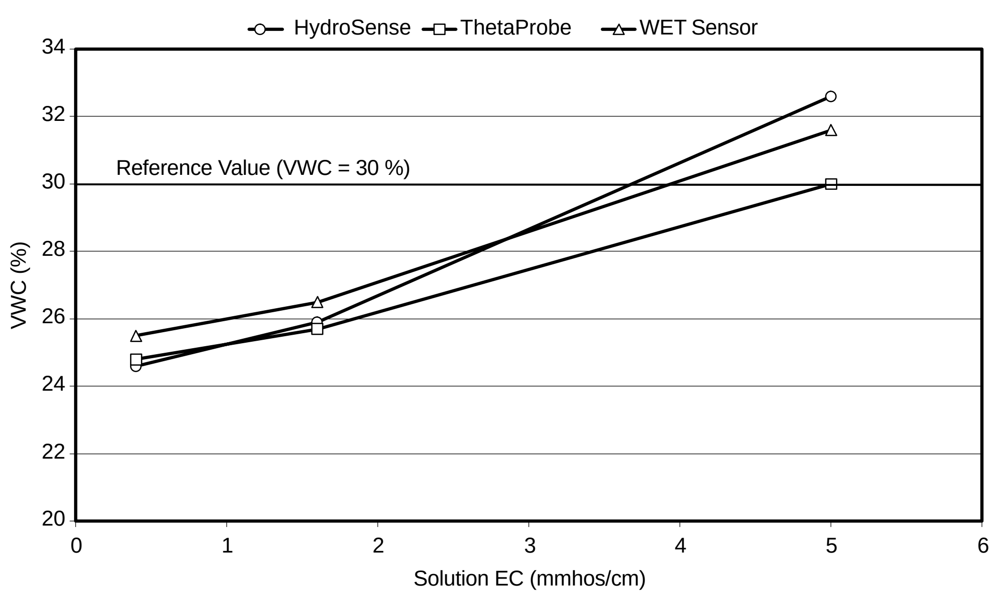

Figure 1. The impact of EC on bias results compared for three sensors.

Table 6. Record of measurements (% VWC) for three appraisers who used the HydroSense to randomly assess the VWC of 10 pots for a series of three trials. [a]

Trial No.	Pot No. 1	2	3	4	5	6	7	8	9	10	Averages
	Appraiser A										
1	14.6	22.6	17.4	28.7	10.2	31.5	37.0	36.3	63.3	12.7	
2	14.0	22.1	16.3	27.8	8.8	30.5	35.3	35.8	56.0	12.1	
3	13.4	20.8	17.4	26.3	9.5	31.3	35.6	35.6	59.7	12.1	
Average	14.0	21.8	17.0	27.6	9.5	31.1	36.0	35.9	59.6	12.3	26.5
Range	1.2	1.7	1.1	2.4	1.4	1.1	1.7	0.7	7.3	0.6	1.9
	Appraiser B										
1	14.0	21.7	17.9	27.8	10.2	33.2	37.3	36.5	63.7	13.4	
2	14.6	23.0	17.4	28.1	10.2	32.7	38.0	35.8	67.5	12.1	
3	14.0	22.1	16.8	28.4	9.5	33.0	35.6	37.0	63.2	12.1	
Average	14.2	22.3	17.4	28.1	9.9	32.9	36.9	36.5	64.8	12.5	27.5
Range	0.6	1.3	1.1	0.6	0.7	0.5	2.5	1.2	4.3	1.2	1.4
	Appraiser C										
1	15.7	22.9	17.9	29.2	10.2	33.2	37.5	36.5	68.5	13.4	
2	14.0	23.3	16.8	28.4	10.2	33.2	36.8	35.1	68.9	13.4	
3	14.6	23.3	16.8	28.4	10.2	32.5	37.5	36.3	65.8	12.7	
Average	14.8	23.2	17.2	28.6	10.2	32.9	37.3	36.0	67.7	13.2	28.1
Range	1.8	0.4	1.1	0.8	0.0	0.7	0.8	1.4	3.0	0.6	1.1

[a] Each measurement is the average of three probings.

Table 7. Record of measurements (% VWC) for three appraisers who used the ThetaProbe to randomly assess the VWC of 10 pots for a series of three trials.[a]

Trial No.	Pot No. 1	2	3	4	5	6	7	8	9	10	Averages
	Appraiser A										
1	14.5	20.5	17.4	23.9	9.0	27.6	30.7	36.4	41.3	12.2	
2	13.1	19.5	14.4	22.2	8.1	24.6	30.6	33.8	41.6	11.8	
3	11.4	19.1	14.5	23.5	7.0	28.1	32.2	30.4	39.9	12.1	
Average	13.0	19.7	15.5	23.2	8.0	26.8	31.2	33.5	40.9	12.0	22.4
Range	3.1	1.4	3.0	1.7	2.0	3.5	1.6	6.1	1.7	0.4	2.5
	Appraiser B										
1	13.3	20.7	16.5	24.7	9.2	29.9	32.5	38.3	44.0	12.0	
2	13.2	20.2	16.4	24.7	8.6	29.3	32.6	37.6	43.5	13.8	
3	13.2	20.6	17.2	23.6	9.1	27.4	32.2	34.7	43.7	12.8	
Average	13.2	20.5	16.7	24.3	9.0	28.9	32.5	36.9	43.7	12.9	23.9
Range	0.1	0.6	0.8	1.1	0.6	2.5	0.4	3.6	0.5	1.8	1.2
	Appraiser C										
1	13.3	21.3	17.2	25.5	9.2	29.6	33.5	35.9	43.2	13.3	
2	13.5	21.8	17.1	26.6	9.2	29.9	34.0	36.5	44.8	13.1	
3	13.8	20.6	16.9	26.1	9.1	28.5	31.5	36.5	43.6	12.8	
Average	13.5	21.2	17.1	26.0	9.2	29.3	33.0	36.3	43.8	13.1	24.3
Range	0.4	1.2	0.3	1.1	0.1	1.4	2.5	0.6	1.6	0.5	1.0

[a] Each measurement is the average of three probings.

Table 8. Record of measurements (% VWC) for three appraisers who used the WET Sensor to randomly assess the VWC of 10 pots for a series of three trials.[a]

Trial No.	Pot No. 1	2	3	4	5	6	7	8	9	10	Averages
	Appraiser A										
1	10.6	19.5	14.9	25.8	4.8	29.1	32.0	34.7	50.7	10.0	
2	11.7	22.4	15.1	26.7	5.3	27.2	34.3	34.3	48.7	10.6	
3	11.6	18.1	13.9	24.4	5.9	29.2	29.8	34.4	46.3	10.8	
Average	11.3	20.0	14.6	25.6	5.3	28.5	32.0	34.5	48.6	10.5	23.1
Range	1.1	4.3	1.1	2.3	1.1	2.0	4.5	0.4	4.5	0.7	2.2
	Appraiser B										
1	12.5	22.5	17.2	25.3	6.1	31.6	36.3	37.1	50.9	10.7	
2	10.2	19.4	13.8	22.7	5.3	28.1	32.9	34.5	48.3	9.0	
3	12.0	20.4	15.2	25.6	6.1	30.5	34.7	39.5	50.4	10.7	
Average	11.6	20.8	15.4	24.5	5.8	30.1	34.6	37.0	49.9	10.2	24.0
Range	2.3	3.2	3.5	2.9	0.9	3.5	3.3	5.1	2.6	1.7	2.9
	Appraiser C										
1	13.1	24.6	17.9	28.1	6.2	35.2	39.4	39.4	55.5	12.5	
2	12.0	22.9	15.1	26.8	6.8	29.2	37.3	40.1	52.2	11.6	
3	11.9	20.7	15.7	25.1	6.8	31.2	35.8	37.5	51.5	11.7	
Average	12.3	22.8	16.2	26.7	6.6	31.9	37.5	39.0	53.1	11.9	25.8
Range	1.3	3.9	2.7	3.1	0.6	6.0	3.6	2.6	4.1	0.9	2.9

[a] Each measurement is the average of three probings.

increases, the value of d_2^* increases leading to a lower estimate of standard deviation. But, as the number of containers and the number of appraisers increase, the value of d_2^* decreases leading to a higher estimate of standard deviation. [See Grant and Leavenworth (1988) or Juran and Gryna (1993) for additional clarification and justification for using average range and d_2^* to estimate standard deviation.]

A final measure of equipment variation is determined by calculating a 99% confidence interval for instrument readings.

$$\begin{aligned} EV &= 5.15\,\hat{\sigma}_e \\ &= 5.15 \times 0.87\% \\ &= 4.48\% \end{aligned} \tag{3}$$

In other words, in spite of measurement variation caused by operational limitations or flaws in the sensor itself, if the HydroSense were used to measure the VWC of a single container of medium an infinite number of times, we can be 99% confident the distribution of this array of measurements would be within an interval bounded by ±2.24%, assuming the readings are normally distributed (5.15 sample standard deviations define the area under a normal distribution curve equal to 99%).

Appraiser Variation (AV) – Reproducibility

The capability of appraisers to reproduce the same readings over three trials is calculated by accounting for the difference between the average of all readings obtained by Appraiser A $(\overline{X}_A)$ for all three trials compared to the average of all readings for Appraiser B $(\overline{X}_B)$ and Appraiser C $(\overline{X}_C)$.

The maximum difference (or range) between the three averages $(R_{\overline{X}})$ for the HydroSense is obtained from values shown in table 6.

$\overline{X}_A = 26.5\%$

$\overline{X}_B = 27.5\%$

$\overline{X}_C = 28.1\%$

$$\begin{aligned} R_{\overline{X}} &= \text{Max}\overline{X} - \text{Min}\overline{X} \\ &= \overline{X}_C - \overline{X}_A \\ &= 28.1\% - 26.5\% \\ &= 1.6\% \end{aligned} \tag{4}$$

The appraiser standard deviation is estimated:

$$\begin{aligned} \hat{\sigma}_a &= \frac{R_{\overline{X}}}{d_2^*} \\ &= \frac{1.61\%}{1.91} \\ &= 0.84\ \% \end{aligned} \tag{5}$$

A final measure of appraiser variation is determined by calculating a 99% confidence interval for appraiser readings (assuming a population of readings is normally distributed).

$$\begin{aligned} AV &= 5.15\ \hat{\sigma}_a \\ &= 5.15 \times 0.84\% \\ &= 4.33\% \end{aligned} \tag{6}$$

This result says, due to unique, individual behaviors of qualified appraisers, measurement results would be subjected to a second component of measurement variation along with equipment variation. But, we can be 99% confident the distribution of this array of measurements would be within an interval bounded by ±2.17%.

Measurement Error – Repeatability and Reproducibility (R&R)

An overall indication of measurement system error (R&R) that accounts for the combined effects of instrument repeatability and operator reproducibility can be determined. Using values for the HydroSense calculated from equation 2 and 5:

$$\begin{aligned} \hat{\sigma}_{R\&R} &= \sqrt{\hat{\sigma}_e^2 + \hat{\sigma}_a^2} \\ &= \sqrt{(0.87\%)^2 + (0.84\%)^2} \\ &= 1.21\% \end{aligned} \tag{7}$$

A final perspective on measurement system error is determined by calculating a third 99% confidence interval. The result shows we can be 99% confident a normally distributed measurement error would be bounded by the interval ±3.12%.

$$\begin{aligned} R\&R &= 5.15\ \hat{\sigma}_{R\&R} \\ &= 5.15 \times 1.21\% \\ &= 6.23\% \end{aligned} \tag{8}$$

Discrimination

The capability of the HydroSense to reliably discern differences in container media VWC can be quantified by comparing measurement error to the range of expected values that are to be measured. A measurement system will have adequate discrimination if its apparent resolution is small relative to the range of measurements to be discerned. The upper limit for the VWC of commercially available potting mediums used for landscape nursery crops is on the order of 50%. Any water applied to a potting medium above 50% VWC will typically migrate to the bottom of the container and settle there or leach out. When a medium is completely dry the VWC will be approximately 0%. Therefore, the range of expected values (R_{ev}) to be discriminated is 50. Measurement system acceptability (MSA) can be defined by equation 9.

$$\begin{aligned} MSA &= \frac{R\&R}{Rev} \\ &= \frac{6.23\%}{50} \\ &= 12.5\% \end{aligned} \tag{9}$$

Down et al. (1995) suggest the following guidelines for evaluating MSA. These guidelines are recognized and accepted by the American Society for Quality:

- MSA under 10% – the measurement system is acceptable
- MSA 10% to 30% – the measurement system may be acceptable based on application criticality
- MSA over 30% – the measurement system needs improvement

Whether or not a measurement system is acceptable depends on many factors such as the criticality of the measured characteristic, appraiser influence, environment, available measurement technology, etc., so the guidelines are general. Expected day to day variations in sunlight, rainfall, and potting medium conditions would preclude a requirement for unattainably and needlessly precise assessments of VWC for landscape nursery crops. But, consistent, objective quantifications of container moisture levels would be invaluable to growers compared to the subjective assessments that are currently used.

Equipment variation, appraiser variation, and measurement system error were calculated for all three sensors and recorded in table 9. The results indicate measurement error for the WET Sensor was 2.11% VWC while the HydroSense and the ThetaProbe were 1.21% and 1.43%, respectively. Correspondingly, the 99% confidence interval for the WET Sensor was ±5.44% VWC while the HydroSense and the ThetaProbe were ±3.12% and ±3.45%, respectively. The equipment component and the appraiser component of measurement system variation were nearly the same for each sensor. MSA levels were found to be acceptable for all three sensors based on application criticality: 21.7% for the WET Sensor, 13.8% for the ThetaProbe and 12.5% for the HydroSense.

General Comments

Review of VWC readings for each pot in table 10 indicates, in almost every instance, all three sensors and all three appraisers distinguished the sequential order of potting medium moisture contents ranging from 5% to 50% VWC (as shown in table 1) including a correct assessment of the comparative difference between Pot No. 1 at 10% VWC and Pot No. 10 at 9% VWC. Table 10 also shows that the readings obtained by Appraiser A, in all instances, were less than the readings obtained by Appraiser B except for two instances (WET Sensor readings for Pot No. 4 and Pot No. 10). Similarly, the readings obtained by Appraiser B were less than the readings obtained by Appraiser C, with the exception of three instances (HydroSense readings for Pot No. 3 and 8) and the ThetaProbe reading for Pot No. 8 with one reading being identical (HydroSense reading for Pot No. 6). These data suggested readings were significantly affected in some way by operator technique. For example, figure 2 shows VWC readings from the ThetaProbe obtained for three trials as a function of each appraiser and pot number. The slope of each set of lines indicates that typically readings for

Table 9. Summary of instrument repeatability, reproducibility, and MSA calculations for all three instruments.

Instrument	Repeatability	Reproducibility	Measurement Error	Measurement System Acceptability (%)
	Estimated Standard Deviation (% VWC)			
HydroSense	0.86	0.84	1.21	12.5
ThetaProbe	0.91	0.99	1.34	13.8
WET Sensor	1.57	1.41	2.11	21.7
	99 % Confidence Interval (% VWC)			
HydroSense	± 2.22	± 2.17	± 3.12	
ThetaProbe	± 2.35	± 2.55	± 3.45	
WET Sensor	± 4.05	± 3.63	± 5.44	

Appraiser A were less than Appraiser B and readings for Appraiser B were less than Appraiser C (except for Pot No. 8). Similarly, figure 3 illustrates comparable results from a preliminary experiment. Appraiser B was consistently recording measurements 10% above Appraiser C. While observing operator technique, it was noted that Appraiser B typically probed the media more rapidly and vigorously than either Appraiser A or Appraiser C. Therefore, the potting medium was being compressed at the point of impact leading to higher moisture readings.

Differences in the operational characteristics of the three sensors should be noted. The HydroSense probe consisted of two rods 12 cm in length compared to an array of four rods 6 cm long for the ThetaProbe and three rods 6.35 cm long for the WET Sensor. Particularly in samples with higher water contents, remnants of medium stuck between the rods more tenaciously within the array of four rods employed by the ThetaProbe and the three rods employed by the WET Sensor than within the two rods used by the HydroSense. The wet medium had to be dislodged with a soft paint brush before moving to the next pot. The HydroSense also had the advantage of sensing a cylindrical cross section of the potting medium that was twice as long at the other two leading to a more representative sample.

A final observation from tables 6, 7, and 8 was evidence that for Appraisers A and B, the VWC readings for the HydroSense were nearly always higher than the WET Sensor readings, and similarly, the WET Senor readings were nearly always higher than the ThetaProbe readings. This occurred for all three trials. The same observation was only occasionally true for Appraiser C.

Summary and Conclusions

If decisions are to be made concerning "When to irrigate?" and "How much to irrigate?" container-grown plants, then procedures for measuring the accuracy and reliability ofVolumetric Water Content (VWC) sensors should be developed. The benefits attained by using data-based procedures are largely determined by the quality of the measurement data obtained. The quality of measurement data is defined by the statistical properties of multiple measurements observed under stable operating conditions. Three

Table 10. Average of all measurements (% VWC) of each pot number as a function of appraiser and instrument used. The difference between the largest average and the smallest average is the 'Range' shown in the last column

Appraiser	Pot No. 1	2	3	4	5	6	7	8	9	10	Range
	HydroSense										
A	14.0	21.8	17.0	27.6	9.5	31.1	36.0	35.9	59.6	12.3	
B	14.2	22.3	17.4	28.1	9.9	32.9	36.9	36.5	64.8	12.5	
C	14.8	23.2	17.2	28.6	10.2	32.9	37.3	36.0	67.7	13.2	
Average	14.3	22.4	17.2	28.1	9.9	32.3	36.7	36.1	64.1	12.7	54.2
	ThetaProbe										
A	13.0	19.7	15.5	23.2	8.0	26.8	31.2	33.5	40.9	12.0	
B	13.2	20.5	16.7	24.3	9.0	28.9	32.5	36.9	43.7	12.9	
C	13.5	21.2	17.1	26.0	9.2	29.3	33.0	36.3	43.8	13.1	
Average	13.3	20.5	16.4	24.5	8.7	28.3	32.2	35.6	42.8	12.7	34.1
	WET Sensor										
A	11.3	20.0	14.6	25.6	5.3	28.5	32.0	34.5	48.6	10.5	
B	11.6	20.8	15.4	24.5	5.8	30.1	34.6	37.0	49.9	10.2	
C	12.3	22.8	16.2	26.7	6.6	31.9	37.5	39.0	53.1	11.9	
Average	11.7	21.2	15.4	25.6	5.9	30.1	34.7	36.8	50.5	10.9	44.6

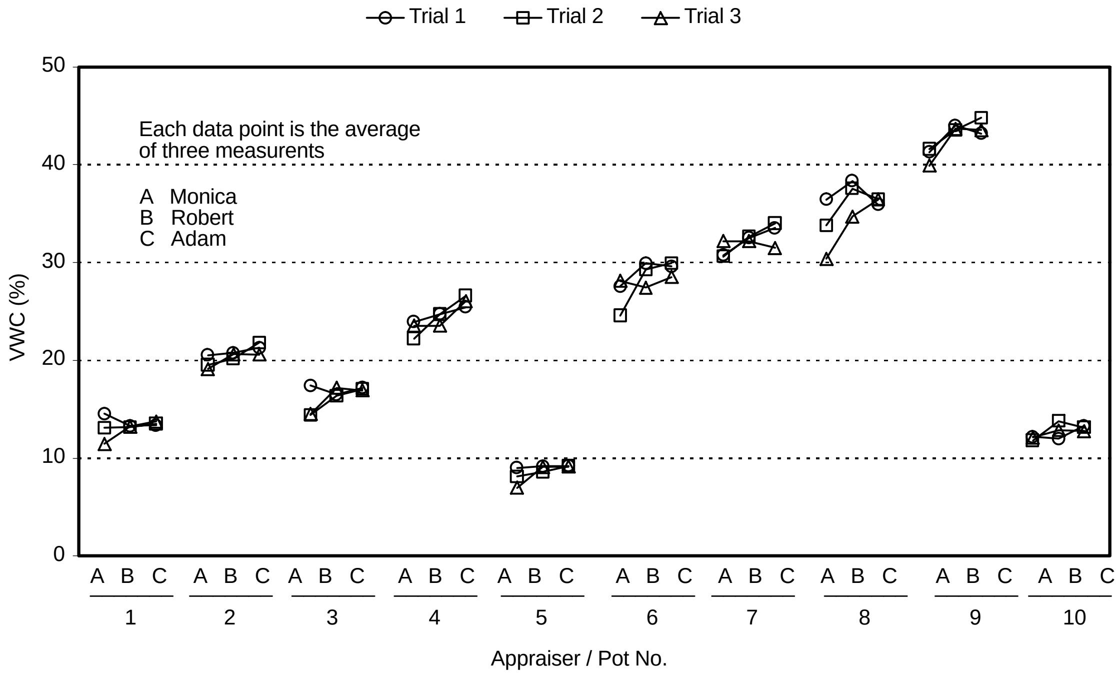

Figure 2. The effects of appraiser technique on VWC readings for 10 levels of moisture in potting mediums while using the ThetaProbe (Data collected 24 Dec. 2003).

statistical properties were used to characterize the quality of data for this study: (1) bias, (2) variance, and (3) measurement system discrimination.

Instrument or sensor bias is defined as the difference between the average of 10 to 20 instrument measurements of a master part and its known value or reference value. Measurement system variance can be determined by calculating: (1) repeatability and (2) reproducibility (Down et al., 1995). Finally, measurement system discrimination refers to the capability of the measurement process to faithfully detect small changes in a measured characteristic. The primary purpose of this research was to establish a statistical procedure for evaluating and comparing the measurement capability of VWC sensors. The objectives of the tests to be reported here were to evaluate the measurement capability of three commercially available moisture sensors that are designed to detect the volumetric water content of potting mediums.

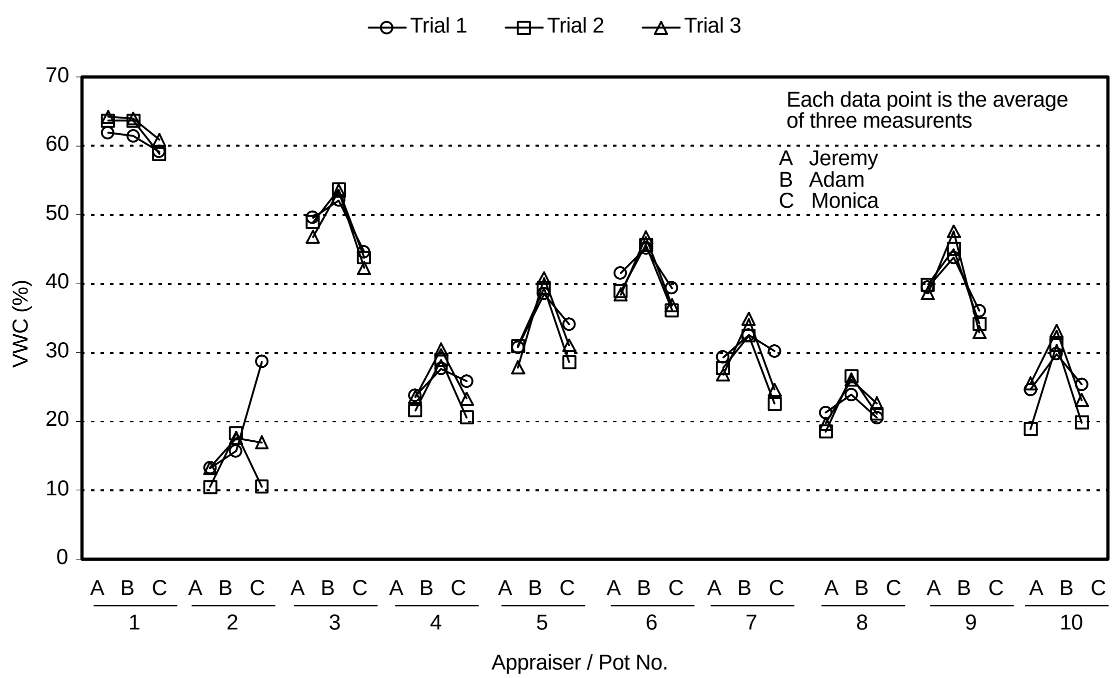

Figure 3. The effects of appraiser technique on VWC readings for 10 levels of moisture in potting mediums while using the ThetaProbe (Data collected 18 Dec. 2003).

Bias readings for all three instruments were 3% to 5% below a 30% VWC reference value defined by a Premier Pro-Mix ‘BX’ potting medium containing tap water with an EC = 0.4 mmhos/cm. When the tap water was amended with calcium nitrate leading to an EC = 5.0 mmhos/cm, the bias was zero for the ThetaProbe, +2.6% for the HydroSense, and +1.6% for the WET Sensor.

Based on specified repeatability and reproducibility measurement procedures for measuring variance, estimated standard deviation (measurement error) for the WET Sensor was 2.11% VWC while the HydroSense and the ThetaProbe were 1.21% and 1.43%, respectively. Evaluation measurement system discrimination in terms of MSA calculations found all three sensors were well within the 10% to 30% guideline that compares measurement error to the range of expected values to be discriminated.

In samples with higher water contents, remnants of medium stuck between the rods more tenaciously within the array of four rods employed by the ThetaProbe and the three rods employed by the WET Sensor than within the two rods used by the HydroSense. The wet medium had to be dislodged with a soft paint brush before moving to the next pot. The HydroSense also had the advantage of sensing a cylindrical cross section of the potting medium that was twice as long as the other two leading to a more representative sample.

Review of VWC readings for each of 10 pots indicates, in every instance, all three sensors and all three appraisers distinguished the sequential order of potting medium moisture contents ranging from 5% to 50% VWC including a correct assessment of the comparative difference between Pot No. 1 at 10% VWC and Pot No. 10 at 9% VWC. Meanwhile, differences in appraiser technique led to 10% higher readings while using the ThetaProbe.

Impact

Nursery crop growers need reliable, capable instruments for measuring key characteristics of a large variety of soilless container mediums and associated suspended solutions used for growing plants and trees. Measuring and documenting the capability of commercially available instruments to accurately and reliably monitor water and nutrients delivered to outdoor, container-grown landscape nursery plants will allow growers to: (1) minimize the use of these valuable resources, (2) minimize wasteful discharge to the surrounding environment, and (3) maximize plant growth and viability.

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